A HV Pulse Generator for PEF Applications

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***Abstract*— In this work, a high voltage (HV) pulse generator for pulsed electric fields (PEF) application in treatment of liquid food is presented. A complete overview of the target application is followed by a detailed analysis and design of a 10 stages Marx generator. The pulse generator uses semiconductor switches to generate up to 30kV pulses of 2µs and 2400Hz frequency. Simulation of the electrical characteristics of the pulse generator and of the electric field, and temperature variations inside the chamber are presented as well as measured results of a 3-stage prototype.**

***Index Terms*— HV Pulse Generator, Marx Generator, PEF.**

I. Introduction

PULSED Electric Fields (PEF) is a relative new procedure, which is being suggested as an alternative to traditional food treatment procedures, such as pasteurization [1]. PEF basically consist in applying one or several very high voltage (HV) pulses of very short duration (20kV and 2µs for example) to a treatment chamber in which the food being treated either flows (for continued flow chambers) or remains static in batches. Applying these pulses to either chamber generates an electric field, which destroys the membrane of most bacteria. This kind of procedure improves the quality of the food as lower temperatures are reached compared to standard pasteurization.

This paper will discuss all the necessary components to implement a PEF system, but will be focused on the design of the pulse generator, the implemented prototype and the obtained results. Different foods result in varying requirements for the pulse generators, depending in the food characteristics such as conductivity and density. The foods selected for this application were milk, grape juice and orange juice. To the best of our knowledge this type of procedure has not been applied in Latin America yet, and can provide an added value for the foods industries in our region.

This paper will first describe the whole system, continuing with the description of each stage of the complete PEF system. Finally the electrical design of the pulse generator and the measured result of the implemented prototype will be discussed.

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II. Complete System

In Fig. 1, a complete system with continued flow is depicted. Its main components are a pump for circulating the liquid food, a pre-heating system, a HV pulse generator and the treatment chamber. The pump maintains a steady flow of untreated food through the chamber (in this case 4L/min); according to [1], optimum results are obtained if the food is pre-heated to 37ºC before applying the HV pulses, therefore the liquid is pre-heated to this temperature. Finally, the liquid flows through a co-field treatment chamber, where the food is treated with PEF. The chamber must be carefully designed to maximize the volume of liquid treated while ensuring that all the liquid was treated. For complete destruction of the bacteria's membranes, 1V voltage over a single cell of circa 1µm or an electric field of E_{Th}=1V/µm is required required and a suggested pulse duration of at least 2µs [1]. Rise and fall times should be as short as possible because all the applied voltage bellow the treatment threshold only increases the food's temperature without destroying the bacteria's membrane. As for the pulse generator, in this work, a Marx generator pulsed with semiconductor switches (IGBT) was implemented.

III. System Design

In this section, the requirements and design considerations for the PEF system are presented. The focus will be on the pulse generator, but the other blocks will also be analyzed, especially when they impact on the design of the former.

A. Food's electrical characteristics

The maximum current the pulse generator must deliver depends on the size and shape of the chamber and the selected food. In order to determine the resistance of the liquid within the treatment chamber, we measured the food's electrical conductivity. In Fig. 2, the measured electrical conductivity of grape juice as a function of temperature is shown. As stated in

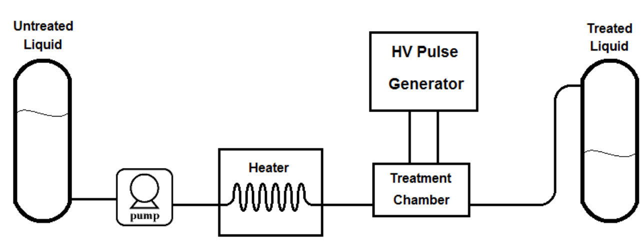

Fig. 1. Block diagram of complete system.

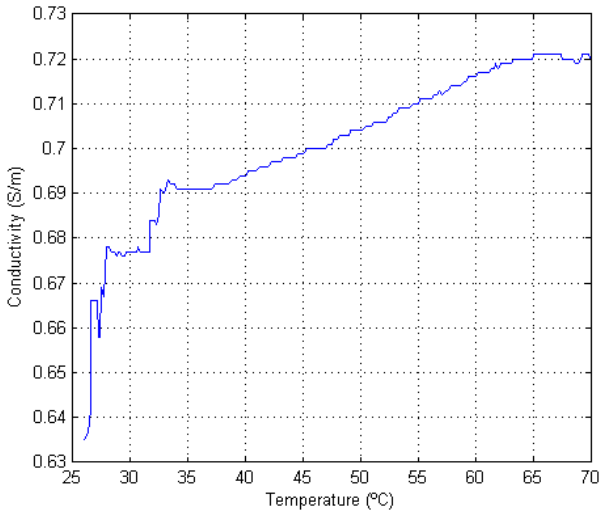

Fig. 2. Conductivity (S/m) vs. Temperature (ºC) grape juice concentrate (Red Globe).

[1], the liquid should be at 37ºC and, to preserve food characteristics, it should never rise past 65ºC. Therefore the electrical conductivity for the Red Globe grape juice concentrate is approximately 0.7 S/m for the expected temperature range. Measures for the other target foods resulted in slightly lower values of conductivity.

B. Co-Field Chamber

The liquid is effectively treated in a cylindrical co-field chamber [2] as shown in Fig. 3. Several alternative chambers were designed, ranging from cylinders of 5.0 mm to 6.2 mm in diameter, and 6.0 mm to 6.5 mm in height. These small chambers must be used for continuous flow chambers, as the volumes range from 117 mm^3 to 187 mm^3. Total resistance of the liquid depends on the exact size and position of the electrodes, and range between 350Ω and 600Ω for the selected chambers. To ensure that the electric field in all the volume is above E_{Th}=1V/µm, electrical pulses of 20kV to 28kV are required. Using Ohm's law, the maximum peak current when the pulse is applied are between 30A and 80A using the best case (20kV and 600Ω) and the worst case (28kV and 350Ω) scenarios respectively.

TABLE I
PULSE PROPERTIES

Property	Value
Maximum Pulse Voltage	30 kV
Maximum Peak Current	100A
Pulse Duration	2 µs
Frequency	2400 Hz

C. Pulse generator

In table I, a summary of the requirements for the pulse generator, derived from the previous subsections is shown. A maximum operating voltage of 30kV and maximum peak current of 100A were selected, for safety reasons.

IV. MARX GENERATOR DESIGN

A Marx pulse generator [3] was selected in this design. The Marx generator consists of several stages, which are charged in parallel, and are discharged in series to generate the HV pulse. Each stage consists of an AC transformer, a rectifier (diode bridge), a HV capacitor, an IGBT switch and a safety diode, as seen in Fig. 4. When the switch is open, each capacitor is charged through the rectifier to its maximum value. When the switch is closed, the voltage appears in the output terminals. Several stages can be connected to generate a HV pulse, when all switches are closed. The safety diode allows for the delivery of a slightly lower pulse in the case of the failure of one of the IGBT switches.

This generator was selected for several reasons. First of all, it allows short pulses with very small rise times. Secondly it is a modular design that can be expanded (or reduced) if a different food is used, and finally because each diode, capacitor and safety switch must withstand only the voltage of each stage, and no switch that withstands the maximum voltage is required.

In [4] a 20kV Marx generator of 22 stages was used for a similar application. But as stated in [3], the efficiency of the Marx generator decreases with the number of stages. To improve efficiency, and using modern solid state switches, a 30kV Marx generator of 10 stages is proposed, in Fig. 5.

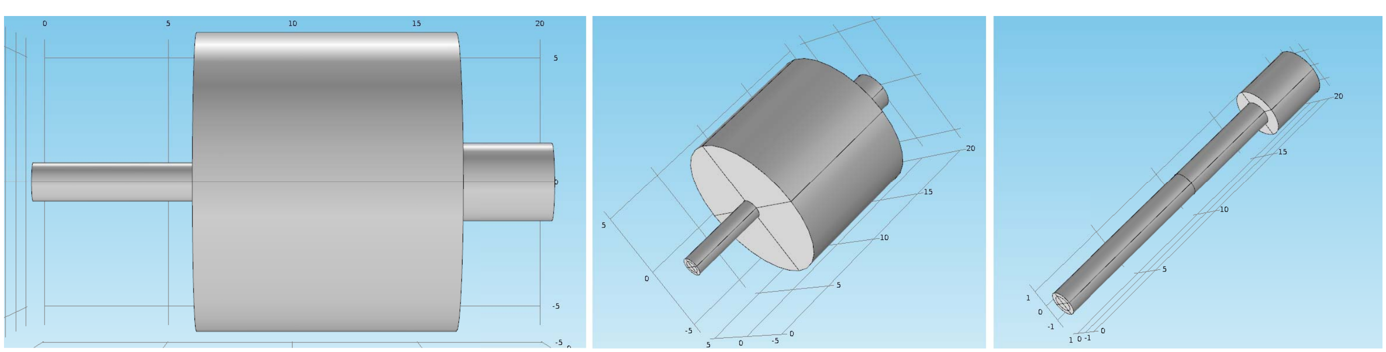

Fig. 3. Treatment chamber. Left shows a XY view featuring the electrode, the isolation material and the ground (from left to right respectively). The middle figure shows a 3D revolution of the model, the liquid flows through the ground pipe throughout the electrode and it is treated in the center of it. The right figure illustrates the chamber without the isolator unveiling a gap which is where the liquid is effectively treated.

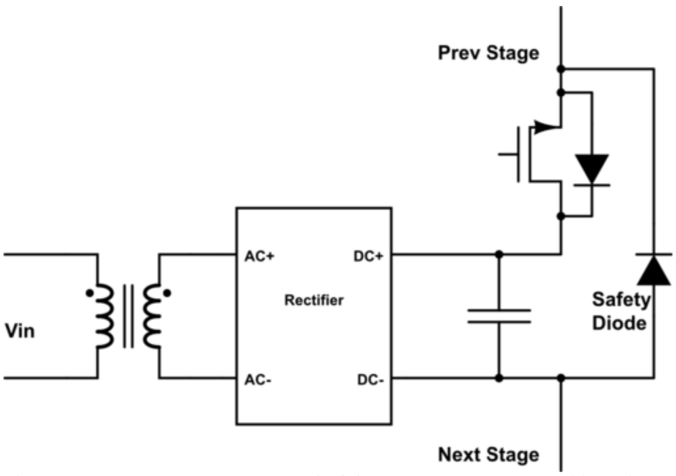

Fig. 4. Marx generator stage. Several of these stages are connected in series to generate the HV pulse.

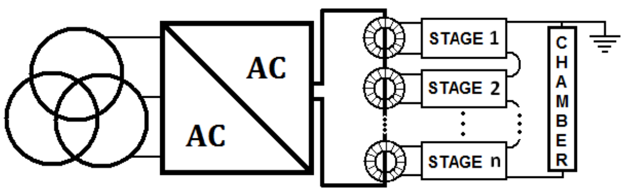

Fig. 5. HV pulse generator.

The complete generator is powered by the standard 380V three-phase. This is first converted using an AC-AC converter to a single phase with higher frequency, to improve efficiency and reduce the stages losses due to wiring. Finally 10 stages like Fig. 4 are connected to generate the HV pulse.

A. AC-AC converter

In Fig. 6, the AC-AC converter selected is shown. The converter is connected to a standard three-phase 380V, and is converted to a single phase of 12.5 kHz frequency of $560V_{peak}$. The control signal for each switch is shown in Fig. 6 (b). The 10 transformers from each stage filter the resulting signal.

B. Marx generator stage

The $560V_{peak}$, 12.5 kHz signal is connected to the 10 stages in series, resulting in a $56V_{peak}$ signal per stage. A high flux ferrite transformer, with a transformation factor of n=53.5, converts the $56V_{peak}$ to a $3000V_{peak}$, which is then rectified using a diode bridge and a capacitor which maintains the voltage at 3000V during the 2µs pulse. The capacitor value was selected, by requiring that the voltage is reduced at most 10% after the 2µs pulse. Using the discharge equation of a RC circuit (1), a minimum value for the capacitor was determined as 52nF.

$$0.9V_0 = V_0 e^{-\frac{2us}{RC}} \quad (1)$$

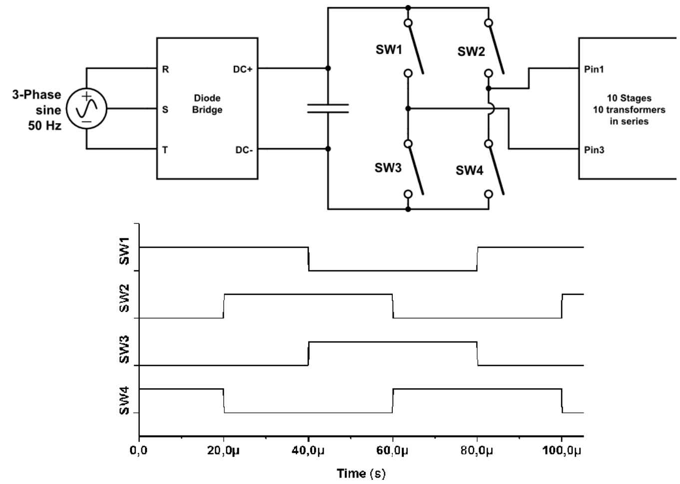

Fig. 6. (a) AC-AC converter schematic. (b) Control signals for each switch.

However, this capacitor is the equivalent capacitor of the 10 stages in series, so a minimum capacitor of 520nF in each stage is required, and an array of four 150nF capacitors was selected [5].

C. HV Switch

Each stage of the Marx generator requires a switch capable of withstanding 3kV when closed and conducting a peak current of 100A. For the continued flow application of 4L/min pulses must have a frequency of at least 2400 Hz to ensure all the liquid is treated with at least 2 pulses (this is flow for a small production for the evaluation of the PEF procedure, if more are required, several chambers can be connected in parallel). A 2µs pulse of 2400Hz, results in a duty cycle of 0.5% and an I_{RMS}=7A. The IXBH12N300 IGBT, from IXYS [6] fulfills all requirements and was selected for this design.

D. Simultaneous triggering

Considering the short duration of the pulse, each stage of the Marx generator must trigger the pulse simultaneously, as only the full voltage pulse will generate enough electric pulse to inoculate the liquid. A single 5V trigger pulse commands the triggering of all stages by using a decoupling toroid ferrite with a single primary input and ten secondary outputs. In each stage, a driving circuit commands the switch. Fig 7 shows the schematic of each stage driver.

For a nearly instantaneous trigger response, a very high relative permeability ferrite with μ_r = 2400 was used in the triggering transformer.

V. Simulations and Measurements

To validate the physical design of the chamber, multi-physics simulations using COMSOL [7] where conducted. In Fig. 8, the module of the electric field inside the chamber when a 30kV pulse is applied is shown. The electric field is large enough for bacteria inactivation inside the whole chamber. One of the advantages of using PEF instead of the traditional pasteurization is the lower temperature that the liquid is exposed (>90ºC in pasteurization).

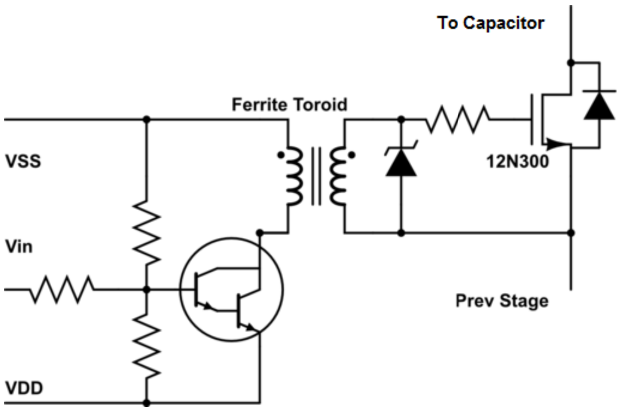

Fig. 7. Schematic of the IGBT driver for each stage.

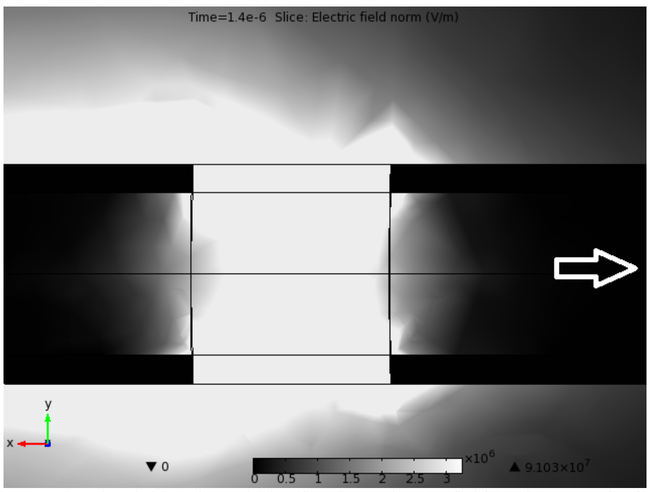

Fig. 8. Electric Field (V/m) within chamber. Electric field is above E_{Th} in the whole chamber

In Fig. 9, the liquid's temperature during standard conditions is shown. The liquid temperature is below 60ºC when leaving the chamber.

In Fig. 10, an electrical simulation of a 10-stage 20kV pulse (2kV in each stage) is shown. Low rise time of 0.25µs and low fall time of 0.6µs show an efficient use of the PEF procedure, while the amplitude loss at the end of the 2µs is below 1.5 kV (7.5%).

As a first step in the implementation of a PEF system, a 3-stage Marx generator was build and tested. Fig. 11 shows a 6kV pulse (2kV in each stage) applied to a test resistance. The maximum theoretical voltage per stage is 3kV but for protection against overshoots, a 2kV stage was tested.

Table II summarize its measured results. Note that in the measurements, parasitic capacitances and resistors increase some of the time constants, but they remain within the specifications.

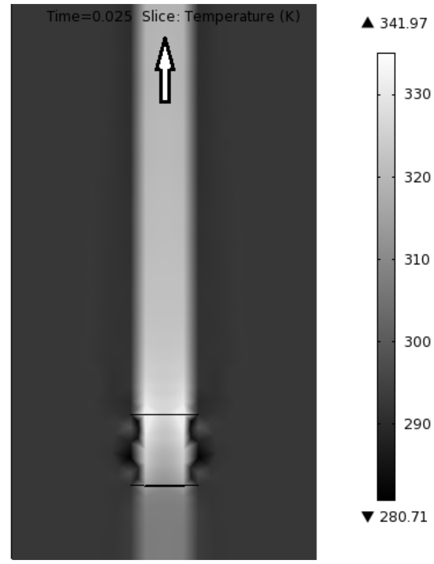

Fig. 9. Temperature (K) gradient along pipe in stationary regimen. Liquid enters at 37ºC and exits at 55ºC.

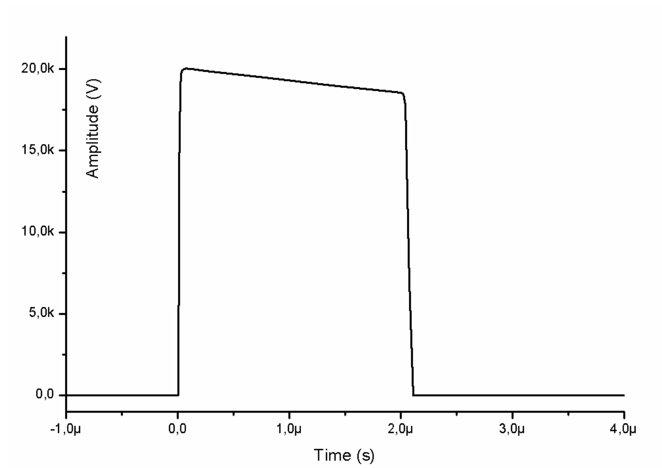

Fig. 10. Pulse simulation of a 10-stage, 2kV per stage.

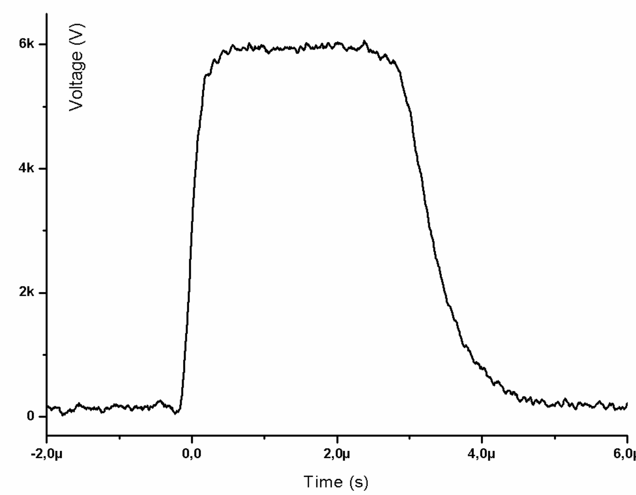

Fig. 11. Pulse measurement of a 3-stage, 2kV per stage prototype.

TABLE II
PULSE MEASUREMENTS

Property	Simulated	Measured
Maximum Pulse Voltage (kV)	6.0	6.0
Average Delay Time (µs)	0.419	0.87
Average Rise Time (µs)	0.249	0.28
Average Fall Time (µs)	0.607	1.2

VI. CONCLUSIONS

A 10 stage Marx pulse generator design for PEF applications was presented. Simulation results show that the design satisfies all the requirements for its use in a 4L/min PEF system for liquid foods (fruit juices for example). A 3-stage prototype was implemented, and measured results concur with the simulations. The design reduces the number of stages compared to previous work, improving overall efficiency.

Further work, including a 10 stages test, and a complete system prototype in collaboration with food engineers are pending of further funding.

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